A graph efficiency multiproduct model of corn/livestock farming: Accounting for nitrate pollution

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This paper estimates a non-parametric production frontier for a population of 117 corn/livestock farms in the Corn Belt region in 1987, employing a hyperbolic graph efficiency approach. There are 7 outputs, 39 variable inputs, 4 fixed inputs, and one "bad" input (residual nitrogen). Three graph efficiency models are estimated. A profit maximization model is specified to estimate a production frontier constrained only by the fixed factors. Two other models involving tax constraints are also estimated. One involves a tax directly on nitrogen and the other involves a tax directly on residual nitrogen, making the disposal of residual nitrogen costly. The nitrogen tax constraint is more effective in reducing residual nitrogen loadings and causes a larger reduction in income than the residual tax constraint.

1. Introduction to the problem

This paper estimates a non-parametric hyperbolic production frontier for 117 corn/livestock farms, a subset of 1,122 farms enumerated in the corn version of the 1987 Farm Cost and Returns Survey (FCRS) conducted by the USDA. These farms accounted for 60% of livestock sales in the Corn Belt (Illinois, Indiana, Iowa, Missouri, and Ohio) in 1987. The mathematical model employed is called the hyperbolic graph efficiency approach and is described in Färe et al. [18]. The estimated model includes 7 outputs, 39 variable inputs, 4 fixed inputs, and one "bad" variable input which is the residual nitrogen from crop and livestock sources. The data for the "bad" variable input were developed by calculating a nitrogen balance for each observation from the survey information.

This agricultural application of the graph efficiency model exploits the high level of detail in the 1987 USDA FCRS survey of corn farmers. The survey contains good statistics on quantities of outputs produced and quantities of inputs used in corn farming, including detailed technical data on corn production, residual nitrogen, and other crop and livestock species that corn/livestock farms jointly produce. Secondary sources were tapped to develop market prices for all outputs, and all corn inputs. Thus, the data set used in this study includes statistical data on market prices for inputs and outputs that each individual corn/livestock farm faces.

With prices and quantities of multiple outputs and multiple inputs available, one feasible profit maximizing approach is the hyperbolic graph efficiency model of the Data Envelopment Analysis (DEA) developed by Färe et al. [17,18]. This approach assumes profit maximization and requires the simultaneous adjustment of both input and output quantities, given input and output prices. While there has been a tremendous amount of research on DEA, the hyperbolic graph efficiency model is not widely known. We know of no other published study exploiting the detailed FCRS production survey and using this information to develop hyperbolic graph efficiency measures in a multiproduct framework.

The data used in this study are from a USDA complex survey of corn farms in the Corn Belt region. Complex surveys used by the USDA are called design based in that they achieve precision estimates of a population's characteristics by selecting the observations using a specific complex statistical design. This design is based on production area clusters and list of producers available to USDA. These so-called design-based surveys have been widely in used in agriculture [21,26] since they have the ability to derive statistics of a highly heterogeneous population with a small sample size. However, statistics computed on design-based surveys do not possess the same properties that characterize statistics from data collected using model-based surveys or so-called random surveys [21,27].[1] Thus, while FCRS survey data can be used to describe multiproduct production, employing conventional parametric techniques to estimate profit or cost functions is not feasible. Fortunately, the nonparametric method used in this study to model the multiproduct firm requires no assumptions on the distribution of the data and is, therefore, suitable for application using USDA complex survey data.

Thus, the objectives of this study are: (1) to describe the ability of the hyperbolic graph efficiency model to reveal the structure of profit efficiency in a common multiproduct agricultural production framework, and (2) to describe the manner in which the USDA complex survey data sets can be used to model joint multiple production and calculate residual nitrate levels from organic and inorganic sources in corn/livestock farming.

The analysis of residual nitrogen loadings in corn/livestock production is of considerable interest because a mounting body of evidence suggests that chemicals

[1] Statistics based on design-based surveys do not possess an asymptotically normally distribited variance-covariance matrix. Single-equation Taylor series approximation techniques have to be employed to linearly approximate the variance-covariance matrix, taking into account the design of the complex survey. The existence of complex error structures in design-based surveys can make the estimation of a system of equations ambiguous [26] since the effects of the complex survey design must be taken into account, especially in a multiproduct framework. This implies that parametric techniques can not be used to estimate standard errors and other statistics of the sample population.

such as nitrate, contained in nitrogen fertilizers and livestock manure, enter water supplies in some regions of the U.S. at potentially harmful levels [25]. Because of limited data, the estimation of residual nitrogen available for leaching from both crop and livestock sources has been only recently conducted for selected States (USDA) [38]. This study exploits data available in the 1987 FCRS survey and calculates the residual nitrogen loadings for each farm in the sample.

The study is organized as follows. A review of the DEA frontier modeling literature is provided in the next section. Section 3 describes the graph efficiency model used in this study. Section 4 describes the nature of the residual nitrogen problem in the Corn Belt region, and the outputs and inputs provided by the 1987 USDA complex survey. The next section presents the application of the graph efficiency model to corn/livestock farming. Some concluding comments are offered in the final section. The appendix describes the procedure used to calculate the residual nitrogen for the sample and for each observation in the data set, and presents three maps: nitrogen use, nitrogen uptake, and residual nitrogen from crop and livestock activities in the entire Corn Belt region.

2. Methodology

Our analysis of farm producer behavior in the Corn Belt is based on a deterministic profit function frontier model. The model uses linear programming methods to construct a frontier technology for measuring overall efficiency for the multiproduct farm. This frontier technology is constructed as a hyperbolic graph efficiency envelopment of the data generated by the set of all corn/livestock farms analyzed. This approach is related to Farrell's original exposition of relative efficiency analysis in 1957 and to the methods developed in the explosion of literature that followed, known as Data Envelopment Analysis (DEA).

2.1. *Modeling the multiproduct firm in agriculture*

Most researchers modeling agricultural production assume profit maximizing competitive behavior as a reasonable starting point in agricultural production. The conventional econometric literature on the analysis of the multiproduct farm is extensive (see Just and Pope [24], Shumway [31], Ball [2], and Chambers and Just [11]).

In contrast to the extensive literature on conventional multiproduct profit function models in agriculture, only a handful of researchers have applied techniques to construct profit frontiers for multiproduct farm (see Thompson et al. [33] and Whittaker [40]).

2.2. *Development of multiproduct approaches*

The initial relative efficiency approach presented by Farrell [19] was cast in terms of a ratio formulation by Charnes, Cooper and Rhodes (CCR) [13]. CCR were the first to formalize the Farrell approach as a set of linear inequalities and to provide an equivalent linear programming formulation to evaluate efficiency. CCR described a mathematical programming formulation for the empirical evaluation of relative efficiency of a Decision Making Unit (DMU) on the basis of the observed quantities of inputs and outputs for a group of similar referent DMUs. They termed this approach Data Envelopment Analysis (DEA). Banker [4] and Banker, Charnes, and Cooper (BCC) [7] provided a formal link between DEA and the estimation of efficient production frontiers through constructs employed in production economics.

Specifically, Banker [5,6] and BCC [7] provided an axiomatic production economics framework for the evaluation of relative efficiency in a setting of multiple outputs. Separate linear programming formulations were developed to assess technical and scale efficiencies and returns to scale. BCC were the first to formalize the Farrell approach as a set of linear inequalities exhibiting varying returns to scale. Banker and Morey [8,9] developed modified models, for selected factors, and relaxed the requirement in DEA models that a constant marginal productivity situation applies.

DEA, as developed by Charnes and Cooper [12] and CCR, does not require any a priori weights of the inputs and outputs. DEA is also value-free, which is both a strength and a weakness, as pointed out by Thompson et al. [33]. It is a strength insofar as it is able to distinguish the DEA technically-efficient DMUs from the DEA technically-inefficient DMUs in the multiple input and multiple output case, without any need for a parametric specification. However, as Thompson et al. [33] pointed out, values (prices/costs) must be introduced into the measurement problem to make it possible to proceed from estimation of technical efficiency towards the estimation of "overall efficiency".

If the DMUs face fixed and known input and output prices for all inputs and outputs, then such overall efficiency measures can be defined relative to these prices (see, for example, Lovell and Schmidt [28]). On the other hand, expanding on the value-free approach of DEA, Thompson et al. [32] specified and estimated bounds for the virtual multipliers and defined a so-called assurance region (AR), which was adjoined to the DEA program.

In sum, DEA is an approach to measuring the efficiency of entities with multiple outputs and multiple inputs which is attractive when there is no information available on prices.

2.3. *Graph efficiency approach*

Färe et al. [17,18] developed and presented a profit maximization approach to efficiency. This approach is called hyperbolic graph efficiency and it requires the simultaneous adjustment of both input and output quantities, given input and output prices.

While there has been wide spread use of DEA techniques, the hyperbolic graph efficiency approach is not widely known. The reason why we chose the graph efficiency approach for the present investigation is the detailed nature of the data resources that are available for agricultural applications in USDA complex survey data.

USDA agricultural survey data not only provide information on all inputs and outputs, but they also include data on the market prices for inputs and outputs facing each individual farm. Thus, the hyperbolic graph efficiency model can be used to depict the maximum obtainable profit by each farm within a miltiproduct framework as a function of input and output prices, given the prevailing technology in the Corn Belt region. As in Färe et al. [18], the model can be developed under variable returns to scale or under constant returns to scale. We chose the former model formulation; prior extensive econometric agricultural modeling efforts indicate that variable returns to scale is more likely to prevail in a single year cross-section when some inputs are fixed (Heady [23], Shumway [31], Chambers and Just [11]).

Also, as in Färe et al. [18], the graph efficiency model can be specified under strong or weak input disposability; we choose the former. Strong or free disposability in inputs refers to the ability of an unwanted commodity to be disposed of with no cost. When an input can be increased without reducing output or disposed of freely, without incurring a cost, then this input satisfies strong disposability. Thus, strong input disposability is a quite strong assumption in the case of chemical fertilizer use, where high levels of residual nitrogen are likely to prevail. It is conceivable that on some livestock farms, total nitrogen applied to corn acres could result in a situation where free disposability of chemical nitrogen plus nitrogen available from livestock waste is not a correct assumption. Clearly, both manure management directives and livestock numbers restrictions would impose economic costs on these livestock operations (see USDA [38]).

The hyperbolic graph technology frontier estimates a frontier technology of all the corn/livestock farms in the sample. Each farm is evaluated with respect to the estimated frontier. The hyperbolic graph efficiency approach is associated with three measures of efficiency (Färe et al. [18]): the graph technical efficiency (Fg), the graph measure of allocative efficiency (Ag), and the graph measure of overall efficiency (Og), with $Og = Ag * Fg$. The graph overall efficiency measure as presented in this paper is defined in Färe et al. [18, pp. 213–214].[2)]

2.4. *Use of DEA to assess impact of environmental taxes*

The relative optimal use of inputs, such as nitrogen, which may contribute to environmental damage, is also captured. Feasible types of policies that aim to address the problem of restricting nitrate use are modeled as imposition of taxes on nitrogen fertilizer use or on residual nitrogen exhibited, ex post.

[2)] Calculation of technical and allocative graph efficiency measures can be developed given the data set analyzed, but this is beyond the main focus of this paper.

Differences in residual nitrogen and nitrogen use categories suggest that environmental policies curbing nitrogen use could have different impacts on the profitability of corn/livestock farms. Environmental loadings of nitrogen fertilizer may differ, depending upon whether a uniform policy focuses on the level of input use or on the amount of residual nitrogen exhibited. One of the environmental problems in Corn Belt agriculture is that residual nitrogen loadings potentially contribute to the contamination of groundwater, but high levels of nitrogen fertilizer do not, necessarily. Therefore, new insights into nitrogen and residual nitrogen use and their effects on profitability of corn/livestock farms is of great importance.

To accomplish our objectives, we estimate technology frontiers with a tax imposed on nitrogen use and a tax imposed on residual nitrogen use. When the results of the estimated technology frontier under profit maximization are compared with the results of the frontiers estimated with the imposed taxes, changes in the overall graph efficiency of the corn/livestock farms due to taxation on nitrogen or on residual nitrogen can easily be assessed. Thus, we calculate both the overall graph efficiency of each corn/livestock farm *with* a tax on nitrogen or a tax on residual nitrogen and the overall graph efficiency of the farm *without* the tax.

3. The model

The nonparametric approach used in this paper is described in Färe et al. [17,18] as a hyperbolic graph efficiency. Farms in the sample are numbered $k = 1,\ldots,K$, using n inputs to produce m outputs. In particular, farm k uses N_{ki} units of input i, $i = 1,\ldots,n$, and produces M_{kj} units of output j, $j = 1,\ldots,m$. To account for the possibility that some of the inputs are fixed, the set of inputs $I = (1,\ldots,n)$ is partitioned into variable inputs, V, and fixed inputs, F, so that $I = (V, F)$. The reference set relative to which hyperbolic graph efficiency will be measured is the graph reference, GR. The graph efficiency reference set satisfying variable returns to scale (V) and strong disposability of inputs (S) can be stated as:

$$(GR \mid V,S) = [(x,u) : u \leq zM, zN \leq x, z \in \mathbb{R}_{+}^{K}], \quad u \in \mathbb{R}_{+}^{M}, x \in \mathbb{R}_{+}^{N}, \tag{1}$$

where z is the vector of intensity variables, $x = (x_1,\ldots,x_n)$ and $u = (u_1,\ldots,u_n)$ denote feasible input and output vectors, respectively.

Since in addition to input and output quantities, input prices and output prices are also available, the short-run technology set for farm k_o under the hyperbolic graph efficiency approach, assuming variable returns to scale, is given by (Färe et al. [18, pp. 212–217]):

$$\prod(r^{k_o}, p_V^{k_o}, N_{k_oF}) = \max\{r^{k_o}u - p_V^{k_o}x_V : (x_V, N_{k_oF}, u) \in T_{k_o}\}$$

$$
\begin{aligned}
= \max\{ & r^{k_o} u - p_V^{k_o} x_V: \\
& \sum z_k M_{kj} \geq u_j, \quad j = 1, \ldots, m, \\
& \sum z_k N_{ki} \leq x_i, \quad i \in V, \\
& \sum z_k N_{ki} \leq N_{k_o i}, \quad i \in F, \\
& \sum z_k = 1, \\
& z_k, x_i, u_j \geq 0, \ k = 1, \ldots, K\},
\end{aligned} \tag{2}
$$

where $x = (x_1, \ldots, x_n)$ and $u = (u_1, \ldots, u_M)$ denote feasible input and output vectors, respectively, and $x_V = (x_i)_{i \in V}$ and $N_{k_oF} = (N_{k_oi})_{i \in F}$ are subvectors of variable and fixed inputs, respectively. $z = (z_1, \ldots, z_K)$ is a vector of activity or intensity levels, $p = (p_1, \ldots, p_n)$ and $r = (r_1, \ldots, r_m)$ denote the vectors of input and output prices, respectively, and $p_V^{k_p} = (p_i^{k_o})_{i \in V}$ is the subvector of variable input prices for farm k_o. It should be noted that $x = (x_1, \ldots, x_n)$ and $u = (u_1, \ldots, u_M)$ are unknowns to be determined in this maximization problem.

The optimal z_k solving (2) must also solve the following[3] problem, applying to farm k:

$$
\begin{aligned}
\prod (r^{k_o}, p_V^{k_o}, N_{k_oF}) &= \max\{r^{k_o} u - p_V^{k_o} x_V: (x_V, N_{k_oF}, u) \in T_{k_o}\} \\
&= \max\{ r^{k_o} z_k M_{kj} - p_V^{k_o} z_k N_{ki}: \\
&\qquad \sum z_k N_{ki} \leq N_{k_oi}, \ i \in F, \\
&\qquad \sum z_k = 1, \\
&\qquad z_k, x_i, u_j \geq 0, \ k = 1, \ldots, K\}.
\end{aligned} \tag{3}
$$

Write the dual to (3) as:

$$
\begin{aligned}
\min\{ & h: \\
& h \geq \sum_j r_j^{k_o} M_{kj} - \sum_i p_i^{k_o} N_{ki}, \quad \text{for } k = 1, \ldots, K \\
& \sum z_{kN_{ki}} \leq N_{k_{oi}}, \ i \in F, \\
& h \ \text{unrestricted in sign}\}.
\end{aligned} \tag{4}
$$

[3] We would like to thank an unknown referee for the developments (3)–(5).

The expression $\sum_j r_j^{k_o} - \sum_i p_i^{k_o} N_{ki}$ can be interpreted as simply the net variable profit of farm k, employing the input and output prices of the farm k_o currently evaluated. The solution to (4) is:

$$h^* = \max\left(\sum_j r_j^{k_o} M_{kj} - \sum_i p_i^{k_o} N_{ki}, \quad \text{for } k = 1, \ldots, K\right), \tag{5}$$

where h^* is the optimal h. It equals the largest profit obtained by any farm, employing the input and output prices of the farm k_o, currently evaluated.

This largest profit may be obtained by one single farm (a unique optimum, with a unique weight $z_k^* = 1$) or by a few farms (alternative optima). By complementary slackness, it follows that if a farm obtains a positive optimal weight $z_k^* > 0$, then the farm also has achieved the largest obtainable profit given by (5).

A tax on nitrogen use is modeled by applying sensitivity analysis and making use of models (3), (4), and (5) above. The purpose of the sensitivity analysis is to measure possible effects on the optimal solution of the profit maximization (model (2)) due to the imposition of tax. Specifically, for farm k_o, a t percent tax on nitrogen use on corn is calculated as the solution to the following model (model (6)):

$$\begin{aligned}
\prod(r^{k_o}, p_V^{k_o}, N_{k_oF}) &= \max\{r^{k_o}u - p_V^{k_o}x_V - tp_n^{k_o}x_n : (x_V N_{k_oF}, u) \in T_{k_o}\} \\
&= \max\{r^{k_o}u - p_V^{k_o}x_V - tp_n^{k_o}x_n : \\
&\qquad \sum z_k M_{kj} \geq u_j, \quad j = 1, \ldots, m, \\
&\qquad \sum z_k N_{ki} \leq x_i, \quad i \in V, \\
&\qquad \sum z_k N_{ki} \leq N_{k_oi}, \; i \in F, \\
&\qquad \sum z_k = 1, \\
&\qquad z_k \geq 0, \; k = 1, \ldots, K\},
\end{aligned} \tag{6}$$

where variable inputs are as in model (2), except that n denotes the nitrogen input used in corn and t denotes the tax on the nitrogen fertilizer. A comparison of model (2) and model (6) shows the profit loss resulting from the imposition of a desired percentage tax on the variable input.

A tax on residual nitrogen, t_{rn}, is modeled similarly to nitrogen use (see model (7) below). In this model, t_{rn} represents a tax or levy in cents per pound on residual nitrogen. The total tax on residual nitrogen by farm is given by $t_{rn} * X_{rn}$. The modeling of a tax on nitrogen in model (6) and on residual nitrogen in model (7) is constructed in such a way as to make the actual tax per pound of nitrogen equal to the tax per pound of residual nitrogen. In other words, a 400% tax on nitrogen in model[4] (6)

[4] See section 5.

corresponds to a 60-cents-per-pound tax on nitrogen and to a 60-cents-per-pound tax on residual nitrogen in model (7).

$$\begin{aligned}\prod(r^{k_o}, p_V^{k_o}, N_{k_oF}) &= \max\{r^{k_o}u - p_V^{k_o}x_V - t_m x_m, N_{k_oF}, u) \in T_{k_o}\}\\ &= \max\{r^{k_o}u - p_V^{k_o}x_V - t_m x_m:\\ &\qquad \textstyle\sum z_k M_{kj} \geq u_j, \quad j = 1, \ldots, m,\\ &\qquad \textstyle\sum z_k N_{ki} \leq x_i, \quad i \in V,\\ &\qquad \textstyle\sum z_k N_{ki} \leq N_{k_oi}, \; i \in F,\\ &\qquad \textstyle\sum z_k = 1,\\ &\qquad z_k \geq 0, \; k = 1, \ldots, K\}, \end{aligned} \tag{7}$$

A comparison of (2) and (7) shows the profit loss resulting from the imposition of a desired percentage tax on the variable input.

4. Data and computational requirements

4.1. *Description of 117 farm sample*

The models described in the previous section are used to estimate technology frontiers of farms in the Corn Belt. Estimation of these frontiers requires detailed data on outputs and inputs, including information on pesticide and nitrogen fertilizer use. A tax on nitrogen fertilizer can produce environmental benefits by decreasing fertilizer use and, under certain circumstances, may be more effective than other policies [30a]. When studying the effect of a chemical tax on environmental loadings, we must take into account chemical, and nonchemical inputs, as well as measures of environmental contaminants.

The data consisted of a subset of 117 farms from the 1,122 corn-producing farms enumerated in the 1987 corn version of the FCRS. The 1987 FCRS is drawn from stratified area and list frames. The corn version was designed to gather statistically representative data on the costs of corn production, along with other production activities and expenditures on corn/livestock farms.

The subset of FCRS data analyzed here represented 47,730 corn/livestock farms in the Corn Belt production region that had greater than \$100 in livestock sales, harvested more than 100 acres of corn, and participated in the government set-aside program. These farms accounted for 60% of livestock sales in the Corn Belt region in 1987. They also represented close to 40% of corn and soybean acreage and 25% of wheat acreage. The sample selection is representative of a significant proportion of agricultural production in the region, and the sample selection changes only the analytic domain while has no effect on the survey design [27].

Seven outputs, corn, soybeans, wheat, sorghum, oats, hay, and livestock, were included in the model and accounted for the entire agricultural output of each farm (see table 1). Additionally, federal payments for land diversion activities were included in output. Field crop output, with the exception of soybeans and wheat, was fed to livestock. Livestock output was measured in dollars of sales, while field crop output was measured in bushels. The State average price for each commodity was taken as the market output price for corn, soybeans, wheat, oats, sorghum, and hay. Total variable input expenses incurred in all crop and livestock activities included (1) own labor and (2) hired labor. The charges to family and operator labor were imputed from hours worked and State wage rates for supervisory labor [35]. Hired labor expenses included cash wages and the reported cash value of noncash benefits. Other total variable input expenses incurred in all crop and livestock activities were (3) fertilizers, (4) pesticides, and (5) energy (fuels and electricity). Fixed inputs included (1) overhead expenses, (2) capital, (3) corn land, and (4) total acres cultivated and in set-aside.

The survey collected data on quantities of fertilizer and pesticide used specifically for corn production. Data on these variable inputs included (1) nitrogen fertilizer, (2) phosphate fertilizer, and (3) potash fertilizer. Fertilizer expenses for corn production were consequently calculated by multiplying the observed quantities by the State-level fertilizer price data [29]. Other total input expenses allocated specifically to corn included (4) 17 herbicides and (5) 9 insecticides. Of the livestock farms surveyed, 99% reported use of nitrogen fertilizer, 95% reported use of some type of herbicide, and 42% reported use of some type of insecticide. The survey provided acre treatments by pesticide. Corn pesticide expenses were calculated by multiplying these quantities used by their respective prices at the national level [1], and the application rates reported by Eichers et al. [16].

4.2. Calculation of residual nitrate for the 117 sample farms

In Kellogg et al. [25], Huang describes a nitrogen budget method for estimating residual nitrogen available for leaching in U.S. crop production. He develops and calculates a nitrogen budget or balance for various crops by relating the amount of nitrate applied on each crop with the amount taken up by the crop; the remaining difference represents the residual amount of nitrate available for leaching or runoff into water supplies.

USDA [34] provides information that measures the level of nitrogen taken up by different kinds of crops and also the nitrate contained in livestock manure or legume credits (table 2). Following Huang, the information in table 2 is used to calculate a nitrogen balance for each of the 117 sample grain/livestock farms. The nitrogen balance calculation for each farm includes an estimate of residual nitrogen loadings, which is used as the "bad" input for each farm (see the appendix).

Table 1

Summary statistics for data.

Item	Mean	Median	Minimum	Maximum
		Production		
Corn (bu)	38,515	29,700	5,550	114,484
Soybeans (bu)	9,122	7,500	0	83,000
Wheat (bu)	1,816	0	0	26,250
Sorghum (bu)	197	0	0	11,088
Oats (bu)	539	0	0	14,000
Hay (bu)	37	0	0	538
Livestock ($)	134,211	67,000	407	1,360,790
Government payments ($)	31,941	28,336	11,000	147,882
		Total expenses ($)		
Own labor	4,668	3,670	1,424	20,004
Hire labor	1,497	232	0	30,000
Fertilizer	22,313	16,745	1,416	172,900
Pesticides	12,313	9,200	160	86,500
Energy	13,375	9,716	1,000	94,400
Overhead	44,624	32,928	4,147	293,845
Capital	38,436	30,444	100	149,099
Livestock expenses	71,494	26,901	125	892,000
Land (acres)	480	526	100	2,892
		Expenses associated with corn production ($)		
Nitrogen	6,072	4,325	0	27,886
Phosphorous	4,322	3,024	0	21,886
Potash	2,504	1,728	0	15,840
Aatrex	423	305	0	3,350
Banvel	84	0	0	2,211
Bicep	789	0	0	7,861
Bladex	327	0	0	3,482
Buctril	133	0	0	4,414
Dual	535	0	0	8,961
Eradicane	143	0	0	7,206
Lasso	482	0	0	9,368
Paraquat	21	0	0	1,297
Prowl	14	0	0	1,646
Princep	15	0	0	1,064
Roundup	40	0	0	2,263
Sutan	181	0	0	7,703
Sutan +	130	0	0	7,274
2, 4-D	8	0	0	531
Lasso-atrazine	281	0	0	7,061
Other herbicides	145	0	0	3,110
Ambush	4	0	0	482
Broot	5	0	0	563
Counter	571	0	0	8,198
Dyfonate	251	0	0	6,824
Furadan	67	0	0	2,871
Lorsban	382	0	0	8,162
Pydrin	8	0	0	961
Thimet	25	0	0	3,030
Other insecticides	78	0	0	4,770

Table 2

Nitrogen content of selected commodities.

Item	Nitrogen
	Percent
Nitrogen applied (uptake)	
Corn (per standard weight per bushel)	1.61
Wheat (per standard weight per bushel)	2.09
Sorghum (per standard weight per bushel)	1.49
Oats (per standard weight per bushel)	1.95
	Pounds
Nitrogen produced (credit)	
Crops	
Soybeans (per bushel)	1.00
Alfalfa hay (per acre)	80.00
Livestock	
Dairy cattle (an adult animal per year)	123.00
Beef cattle (an adult animal per year)	61.00
Pigs (an adult animal per year)	32.00
Sheep (an adult animal per year)	16.00
Chickens (100 per year)	94.00

The tables in the appendix (tables 9–14) clearly indicate that nitrate pollution is a problem associated with both organic and inorganic sources. The sample nitrogen balance, from all sources, is reported in appendix tables 9, 10, and 11, and highlights the significant regional variability of residual nitrogen loadings. The nitrogen balance for each observation further indicates the variability by region in nitrate loadings and the extent to which livestock production contributes to the residual nitrogen loadings (see appendix tables 12, 13, and 14). The estimated residual nitrogen input or "bad" for each observation can be used to trace observations that form the production frontier (see tables 6, 7, and 8).

4.3 *Computational requirements*

The models specification and estimation are accomplished using the General Modeling System (GAMS version 2.25 [10]). Numerical solutions to this problem are computer intensive since there are three models to be estimated and, for each model, every farm is evaluated with respect to the specified frontier. Furthermore, the sensitivity analyses performed for the nitrogen and residual nitrogen tax estimations require intensive computing resources. Our choice of using GAMS over the other available commercial linear programming packages is dictated by the size of the specified production system.

5. Application of the graph efficiency model to corn/livestock farming

Model (2) was used to measure production efficiency frontiers on Corn Belt farms and compare overall graph efficiency and input intensity by fertilizer use level for three Corn Belt regions. Models (6) and (7) were then estimated to measure the economic performance of farms with the imposition of taxes on nitrogen or residual nitrogen. Also, the ratios of the actual nitrogen applied on corn acres to optimal nitrogen use on corn acres, were calculated.

The graph efficiency scores (computed as the positive roots of the quadratic equation shown by Färe et al. [18, p. 214]) and nitrogen input ratios (the ratio of actual nitrogen use on corn acres compared with optimal nitrogen use on corn acres), shown in table 3, indicate some differences in overall economic performance between corn/livestock farmers by region relative to best practice farms in the Corn Belt, and

Table 3

Corn Belt corn/livestock farms: Descriptive statistics by region, 1987.

Variable	Mean	Ohio and Indiana	Iowa and Missouri	Illinois
Observations	117	48	39	30
Profits ($/farm)	93,919.27	88,003.54	100,813.90	94,421.41
Livestock sales ($/farm)	134,211.28	116,757.77	156,103.54	133,676.97
Corn area (acres/farm)	303.84	309.77	315.49	279.20
Soybean area (acres/farm)	231.03	217.06	264.13	210.37
Wheat area (acres/farm)	31.29	45.38	15.05	29.87
Sorghum area (acres/farm)	5.84	1.46	10.82	6.40
Oat area (acres/farm)	30.72	8.69	49.56	41.47
Hay area (acres/farm)	14.82	32.29	16.15	1.03
Corn yield (bushels/acre)	125.59	127.36	126.48	121.60
Corn nitrogen (pounds/acre)	136.20	122.04	142.82	150.28
Corn residual nitrogen (pounds/acre)	91.01	76.99	87.40	118.15
Graph efficiency	0.911	0.922	0.914	0.882
Nitrogen fertilizer (actual/optimal)	1.621	1.608	1.389	1.944

substantially different patterns of efficient use of nitrogen across regions. Examining the overall graph efficiency scores by region, the score for the Ohio/Indiana region was 0.922, compared to 0.882 for farms in Illinois, with farms in Iowa/Missouri region falling in between at 0.914. The ratios of actual to optimal nitrogen fertilizer use were highest on Illinois farms and lowest on Iowa and Missouri farms. In general, corn/livestock farms appear to be substantially overusing chemical nitrogen fertilizer, compared with best practice farms. The computed ratio of actual nitrogen use to optimal use at the mean for the entire sample was 1.621.

Table 3 summarizes the descriptive statistics by region. Because corn/livestock production practices are fairly homogeneous in each region, biases due to differences in technology should be minimal, and probably are accounted for by disaggregating the data regionally. Focus on each type of operation individually also reduces price variation. The extent to which nitrogen fertilizer is a risk-reducing input is another factor that could influence the results, but risk is not included in the model.

The regional categorizations described in table 3 show differences in overall graph efficiency and in the ratios of actual to optimal nitrogen use. This suggests that if taxes are imposed to curb nitrogen use and excess nitrogen loadings, they will have differential impacts on economic activity and environmental loadings of nitrogen fertilizer, depending upon regional differences. It should be noted that these overall graph efficiency scores are derived by estimating one technology frontier for the entire sample.

5.1. Imposition of taxes on nitrogen and residual nitrogen

To examine the impact of a possible environmental restrictions on economic performance and chemical use, model (2) was modified and estimated first with a 400% tax on total nitrogen use (model (6)) and secondly with a 400% tax on residual nitrogen fertilizer (model (7)). The results were compared with the results of model (2). Percentage changes in profits, livestock sales, nitrogen use, and residual nitrogen were calculated by region at the mean (tables 4 and 5). The results of the models *with* the tax depend on those farms that form the frontier. The most efficient farms that form the frontier in the models *with* the environmental tax indicate the existence of farm practices with technologies which use chemical nitrogen fertilizer more efficiently than farms off the frontier. The imposition of taxes, also, serves as a sensitivity analysis or a measure of the robustness to the estimated frontier of the model (2), when nitrogen use changes.

The sensitivity analyses (tax impositions) have different economic and technical impacts depending upon the level of chemical nitrogen fertilizer and the residual nitrogen produced on each farm. The results indicate that the estimated tax-constrained technology frontier differs, depending upon whether a tax is imposed on nitrogen or on residual nitrogen use.

The sensitivity analyses suggest that rather large taxes are required to alter the optimal combinations that formed the profit technology frontier of model (2). When a tax of 200% was imposed, only small changes in the optimal linear combinations of outputs and inputs were observed. Consequently, the sensitivity analysis was carried out with a 250, 300, 350, and 400% tax. When a 400% tax was imposed, then relatively large changes in optimal linear combinations were observed. Two explanations for the size of the taxes required to alter the optimal linear combination of inputs are plausible. First, expenditures on nitrogen fertilizer used on corn production amount to about 10% of total variable costs for the average corn/livestock farm in the sample.

Table 4

Analysis of 400% tax on nitrogen.

Region	Profit	Livestock output	Nitrogen	Residual nitrogen
	Ratio of optimal constrained solution to optimal solution			
	0.808	0.983	0.812	0.822
Ohio/Indiana	0.849	0.972	0.784	0.786
Iowa/Missouri	0.751	1.000	0.845	0.896
Illinois	0.816	0.969	0.808	0.778

Table 5

Analysis of 400% tax on residual nitrogen.

Region	Profit	Livestock output	Nitrogen	Residual nitrogen
	Ratio of optimal constrained solution to optimal solution			
	0.922	0.973	0.842	0.870
Ohio/Indiana	0.947	0.974	0.826	0.850
Iowa/Missouri	0.895	0.986	0.854	0.919
Illinois	0.917	0.959	0.848	0.835

Second, there is relatively little variability in chemical nitrogen use per acre of corn cultivated in the sample under study. Obviously, other samples of corn farms may yield different results. However, this modeling experience is consistent with the conventional econometric literature that indicates a highly inelastic demand for nitrogen fertilizer, in part because nitrogen fertilizer comprises a relatively small proportion of variable expenses. The available literature suggests that rather large taxes are required to induce a decrease in the use of nitrogen fertilizer (Denbaly and Vroomen [14], Dietz and Hoogervorst [15], and Giesen et al. [22]).

5.2. *Regional differences*

The hyperbolic graph efficiency model evaluates the reduction in nitrogen loadings by imposing a tax on nitrogen and a tax on residual nitrogen (see tables 4 and 5 for the sample summary and tables 6, 7, and 8 for each individual farm in the sample). The impact of the two types of taxes differs dramatically by region, illuminating further the site-specific nature of the residual nitrogen problem.

The impact of the two taxes in reducing residual nitrogen loadings is virtually the same on Iowa/Missouri farms, while on Ohio/Indiana and Illinois farms the

Table 6

Impact of nitrogen and residual nitrogen taxes on the use of residual nitrogen on Ohio/Indiana farms.

Livestock sales (dollars)	Corn harvested (acres)	Graph efficiency	Actual residual nitrogen	Profit maximum solution	Nitrogen tax solution	Residual tax solution
				(pounds of residual nitrogen)		
407	150	0.982	12,707	6,817	2,753*	2,753**
2,011	720	1.000	61,808	61,808	61,808	61,808
3,310	168	0.858	8,720	8,740	8,740	8,740
3,600	180	1.000	14,538	14,538	14,538	14,538
4,500	100	0.998	0	20	20	20
4,907	105	0.876	213	20	20	20
6,200	100	1.000	0	0	0	0
6,908	103	1.000	0	0	0	0
7,171	100	1.000	10,255	10,255	10,255	10,255
12,826	149	0.872	0	20	20	20
13,569	105	0.841	0	20	20	20
15,900	158	0.821	1,154	3,847	3,847	3,847
17,000	250	0.734	19,260	19,280	19,280	19,280
18,000	300	0.925	14,526	20,127	20,127	20,127
28,941	625	0.913	14,841	26,829	14,806*	23,496**
30,165	230	0.783	8,310	8,330	8,330	8,330
36,000	160	0.857	11,940	7,034	5,231*	5,231**
36,195	202	0.878	0	20	20	20
41,000	520	0.999	0	20	20	20
47,887	317	0.993	0	20	20	20
50,000	150	0.838	1,259	1,279	1,279	1,279
51,050	141	0.769	11,249	9,984	9,166*	9,166**
51,500	210	0.918	0	20	20	20
67,000	250	1.000	0	0	0	0
70,000	500	0.696	70,026	48,079	0*	759**
74,500	100	0.956	21,301	11,223	11,223	11,223
85,400	400	0.705	38,751	44,104	7,477*	14,385**
99,800	150	0.978	13,932	13,952	10,026*	10,038**
99,915	108	0.929	23,146	10,578	10,578	10,479**
106,506	572	0.999	0	20	20	20
106,906	138	0.999	5,437	5,457	5,457	5,457
107,603	690	1.000	21,050	21,050	21,050	21,050
119,753	412	0.946	52,662	46,272	32,975*	35,654**
123,602	609	0.999	0	20	20	20
134,000	150	0.999	17,155	20	20	20
139,245	375	0.999	0	20	0*	20
142,301	162	0.999	24,070	27,877	27,877	27,877
173,000	600	1.000	0	0	0	0
187,247	289	0.905	38,710	15,152	15,152	15,152
207,713	698	0.884	79,791	21,705	21,705	21,705
229,928	150	0.999	34,759	6,076	6,076	6,076
240,000	340	0.985	64,993	67,013	22,250*	34,173**
349,172	560	0.953	60,979	68,233	26,655*	27,655**
400,100	635	0.899	85,308	74,114	6,025*	6,025**
405,502	250	0.963	71,191	52,774	38,535*	38,535*
410,154	708	1.000	75,193	75,193	75,193	75,193
495,419	600	0.932	46,755	54,018	36,796	36,796

* = change in nitrogen tax solution relative to profit maximum solution.
** = change in residual tax solution relative to profit maximum solution.

Table 7

Impact of nitrogen and residual nitrogen taxes on the use of residual nitrogen on Iowa/Missouri farms.

Livestock sales (dollars)	Corn harvested (acres)	Graph efficiency	Actual residual nitrogen	Profit maximum solution	Nitrogen tax solution	Residual tax solution
				(pounds of residual nitrogen)		
1,296	200	0.999	0	1,593	1,593	1,593
3,560	480	0.764	3,038	4,697	4,697	4,697
3,919	573	0.999	23,102	23,122	23,122	23,122
7,700	280	0.757	52,235	30,867	16,927*	19,084**
10,500	152	0.803	5,349	5,822	5,822	5,822
19,000	105	1.000	5,584	5,874	5,874	5,874
19,920	350	0.633	41,079	11,800	6,135*	9,901**
21,021	110	0.857	2,918	5,805	2,182*	2,182**
27,094	182	0.848	1,685	6,032	6,032	6,032
27,784	136	0.765	11,462	11,639	8,568*	8,568**
28,601	398	0.902	0	4,240	4,240	4,240
30,069	147	0.870	5,762	8,379	8,379	8,379
31,000	400	1.000	7,556	7,556	7,556	7,556
34,010	215	0.999	17,813	17,813	17,813	17,813
38,596	106	1.000	8,658	8,658	8,658	8,658
40,000	241	0.981	6,613	11,485	11,485	11,485
44,502	526	0.834	26,763	25,912	21,806	21,806
45,151	309	0.856	21,057	15,026	12,937*	12,937**
45,613	101	0.995	13,882	13,516	13,516	13,516
57,880	369	1.000	35,483	35,483	35,483	35,483
67,571	121	1.000	8,858	8,858	8,858	8,858
89,450	146	0.911	19,006	19,026	12,524*	12,524**
91,185	477	0.975	47,960	37,026	24,940*	37,026
95,000	450	0.978	34,496	45,313	22,242*	24,552**
98,230	180	0.829	24,032	24,758	19,720*	19,720**
101,292	366	0.810	24,118	17,277	17,277	17,277
103,333	170	0.860	21,603	21,623	18,209*	18,209**
122,606	230	0.941	22,660	27,379	27,379	27,379
136,860	104	1.000	11,603	11,603	11,603	11,603
152,772	160	1.000	20,194	20,194	20,194	20,194
154,000	100	1.000	17,377	17,377	17,377	17,377
179,157	1,100	0.934	94,202	92,370	92,370	92,370
195,730	310	0.859	32,687	35,034	35,034	35,034
271,200	200	0.851	10,657	11,053	11,053	11,053
395,701	377	0.986	78,630	83,719	60,492*	74,131**
460,000	425	1.000	37,569	37,569	37,569	37,569
591,790	647	1.000	0	0	0	0
884,155	811	1.000	82,218	82,218	82,218	82,218
1,360,790	550	1.000	111,273	111,273	111,273	111,273

* = change in nitrogen tax solution relative to profit maximum solution.
** = change in residual tax solution relative to profit maximum solution.

nitrogen tax is much more effective than the residual nitrogen tax in reducing nitrogen loadings. In general, the economic impact of the nitrogen tax is more onerous than that of the residual nitrogen tax in reducing nitrogen loadings. The nitrogen tax has, relatively, greater economic impact on Iowa/Missouri farms than on the rest of

Table 8

Impact of nitrogen and residual nitrogen taxes on the use of residual nitrogen in Illinois.

Livestock sales (dollars)	Corn harvested (acres)	Graph efficiency	Actual residual nitrogen	Profit maximum solution	Nitrogen tax solution	Residual tax solution
				(pounds of residual nitrogen)		
1,210	114	0.929	8,146	409	53*	409
3,690	250	0.724	11,586	11,606	11,606	11,606
12,411	140	0.811	0	20	20	20
15,400	185	0.808	9,269	11,965	11,965	11,965
20,890	210	0.669	33,798	29,331	22,624*	22,624**
23,106	111	0.828	14,461	14,481	2,096*	2,096**
23,445	233	0.723	10,186	14,340	14,340	14,340
23,700	118	0.905	6,959	6,979	6,979	6,979
32,000	313	0.898	14,898	16,236	12,169*	12,169**
39,162	208	1.000	11,397	11,397	11,397	11,397
39,520	320	1.000	33,333	33,333	33,333	33,333
44,800	346	0.941	26,571	31,493	7,626*	7,626**
50,828	320	0.697	33,054	32,969	13,983*	31,901**
61,000	400	0.833	43,410	33,217	16,329*	16,329**
75,000	150	0.977	205	225	225	225
75,592	218	0.893	32,007	0	0	0
94,800	125	0.941	23,403	23,423	18,554*	13,147**
95,283	300	0.826	31,654	26,054	26,054	26,054
119,952	193	0.902	16,546	17,810	17,810	17,810
126,145	565	0.986	36,640	41,848	41,848	41,848
138,900	625	0.999	0	20	20	20
170,297	124	0.888	36,386	15,784	5,931*	5,931**
186,300	315	0.987	48,222	48,242	48,242	48,242
191,143	117	1.000	0	0	0	0
210,781	650	0.809	59,355	61,548	30,717	30,717
268,829	231	0.999	27,655	27,675	27,675	27,675
312,000	697	0.998	53,698	59,960	46,077*	59,960
450,145	375	1.000	74,341	74,341	74,341	74,341
1,100,000	303	1.000	281,604	281,604	281,604	281,604

* = change in nitrogen tax solution relative to profit maximum solution.
** = change in residual tax solution relative to profit maximum solution.

the Corn Belt farms. On the other hand, the residual nitrogen tax has a significantly smaller economic impact on Ohio/Indiana farms than on the rest of the Corn Belt farms.

6. Summary and conclusions

This paper estimates a non-parametric production frontier for a sample of 117 corn/livestock farms in the Corn Belt region in 1987, employing a hyperbolic graph efficiency approach. Furthermore, the paper demonstrates the manner by which USDA complex survey data can be used to model joint production of miltiproduct activities and calculates residual nitrogen from crop and livestock sources.

Three graph efficiency models are estimated. First, a profit maximization model is used to construct a production frontier, constrained only by the fixed factors. The model includes 7 outputs, 39 variable inputs, 4 fixed inputs, and one "bad" input (residual nitrogen). Two models involving tax constraints are estimated; one *with* a tax directly on nitrogen and the other *with* a tax directly on residual nitrogen, making the disposal of residual nitrogen costly. A comparison of the two models indicates that the nitrogen tax constraint is more effective in reducing residual nitrogen loadings than the residual nitrogen tax constraint, but, for comparable taxes, it is also causes a larger reduction in profits than the residual tax constraint.

This agricultural application of the hyperbolic graph efficiency model exploits the high level of detail in the 1987 FCRS survey of corn/livestock farmers in the Corn Belt region. The survey contains good statistics on quantities of outputs produced and quantities of inputs used in corn farming, including detailed technical data on corn production. Secondary sources were tapped to develop market prices for all outputs, and all corn inputs. Thus, the data set used in this study includes statistical data on market prices for inputs and outputs that each individual corn/livestock farm faces. Just as importantly, in terms of accounting for residual nitrogen, this data set also includes detail on all crop and livestock species that corn/livestock farms jointly produce.

Possible extensions and ongoing areas of future research pertaining to the graph efficiency model include relaxing the assumption of free disposability and decomposing the overall graph efficiency in allocative efficiency and technical efficiency. Such extension of the graph technology to include undesirable outputs seems highly promising (see Ball et al. [2]).

Appendix: Residual nitrogen and livestock production

In the United States, the most important form of nitrogen fertilizer is anhydrous ammonia, applied in gaseous form [20]. Other types of liquid and solid types of inorganic nitrogen fertilizers, such as urea, are also applied. Nitrogen also exists in organic sources such as livestock manure, crop residue, and legume fixation. Organic molecules in these nitrogen sources are converted to nitrates through the process of nitrification. Both chemical fertilizer and manure may satisfy the nitrogen requirements of crops, but chemical fertilizer is a more practical source of nitrogen because it can be economically transported and applied at optimum times during the growing season.

In recent decades, U.S. farmers have used higher doses of nitrogen from chemical and manure sources and improved crops to boost yields [38]. However, modern nitrogen use practices have led to levels of nitrogen in the environment that cannot be absorbed by plants, and may contaminate ground and surface water supplies [25]. Available USDA estimates of residual nitrate indicate that nitrogen use on crops from chemical, legume and manure sources was significantly in excess of crop uptake in key Corn Belt states during 1990–1993. In Illinois, the annual excess ranged from 25% to 46%, in Indiana, from 17% to 45%, and in Iowa, from 10% to 48%. The USDA data indicate that, in most instances, nitrogen from inorganic sources far exceeded crop uptake – Indiana and Iowa in 1992 are the only exceptions in the Corn Belt. Thus, nitrogen from livestock sources, in general, adds an amount of nitrogen that must be accommodated in states where inorganic nitrogen use is already in excess of crop needs. During 1990–1993, nitrogen from manure as a proportion of excess nitrogen annually ranged from 4% to 6% in Illinois, 7% to 13% in Indiana, and 10% to 34% in Iowa.

A.1. Trends in livestock and manure production in the Corn Belt

Over the past 15 years, Corn Belt agriculture has witnessed an unprecedented concentration of its livestock production because of an increasingly competitive production environment [39]. While production of most species in the Corn Belt actually moderated or declined between 1975 and 1990, the size and concentration of livestock operations, particularly swine operations, increased dramatically. Thus, while only 11 Iowa counties boosted livestock production from 1975 to 1990, these 11 counties increased their share of nitrogen loadings from livestock in the state from 15% to 21%. Similar trends in concentration occurred in other Corn Belt states.

Figures 1, 2 and 3 reveal the concentration of nitrogen use from chemical fertilizer applications and livestock in the Corn Belt in 1987, and the estimated amount of residual nitrogen loadings.

A.2. Calculation of residual nitrate from crop and livestock production for the 117 sample farms

We proceed by first calculating crop uptake of nitrogen and use of inorganic fertilizers and credits from legumes, omitting nitrogen from manure sources. We then estimate nitrogen from manure sources, by livestock species, and calculate a comprehensive crop/livestock nitrogen balance, by region, and by farm.

The survey provided no historical information on crop rotations. Hence, nitrogen credits from soybeans and alfalfa are allocated to corn land, based on the proportion of corn area relative to total crop area in 1987. For the entire sample, this implies that an acre of corn follows soybeans 35% of the time, and an acre of corn follows alfalfa 6% of the time. These estimates are consistent with available rotation data, which indicate that, on average, 40% of corn acres follow soybeans in the Corn Belt [36]. Where corn/alfalfa rotations are prevalent, as in Wisconsin, corn follows alfalfa 12% of the time. Thus, the nitrogen credit assumptions for soybeans and alfalfa appear reasonable.

The estimated amounts of nitrogen from inorganic fertilizers, soybeans and alfalfa, and the estimated uptakes of nitrogen by crop are presented in table 9. About

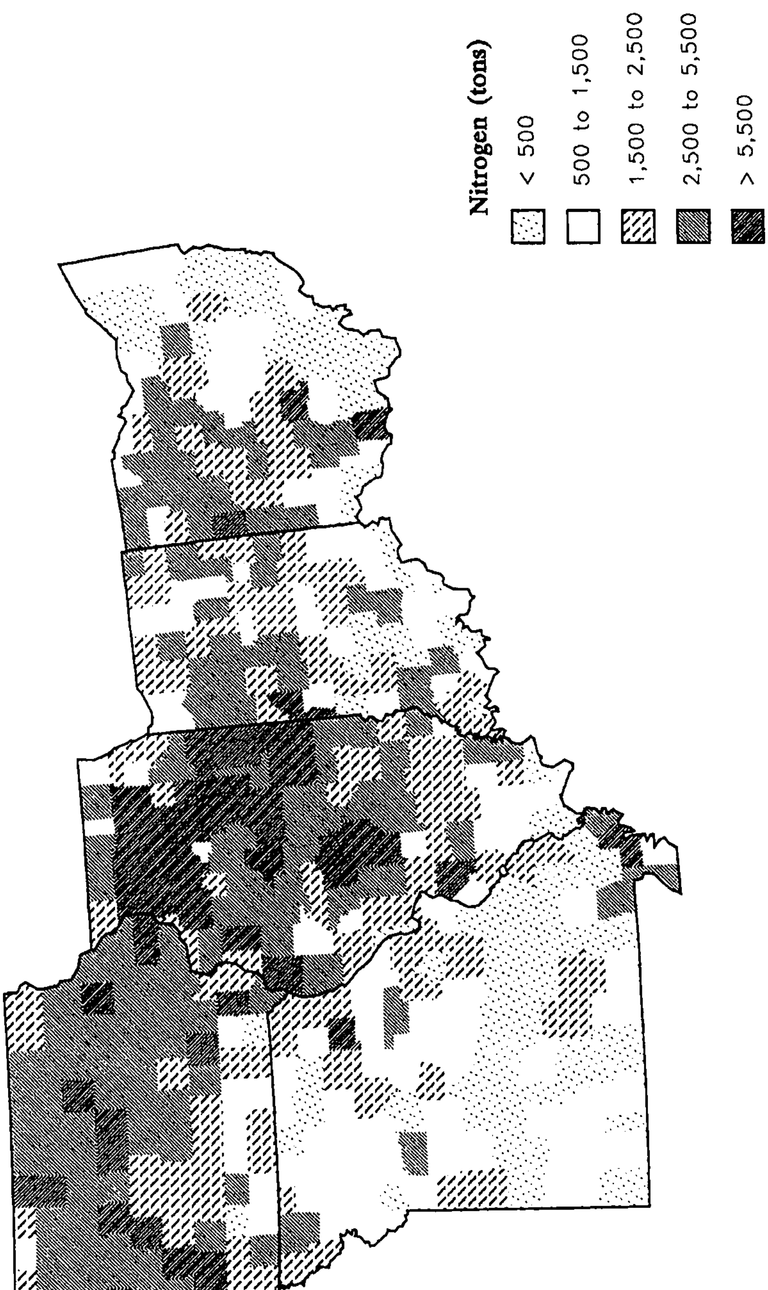

Figure 1. Loadings of chemical nitrogen on corn production in the U.S. Corn Belt region, 1987.

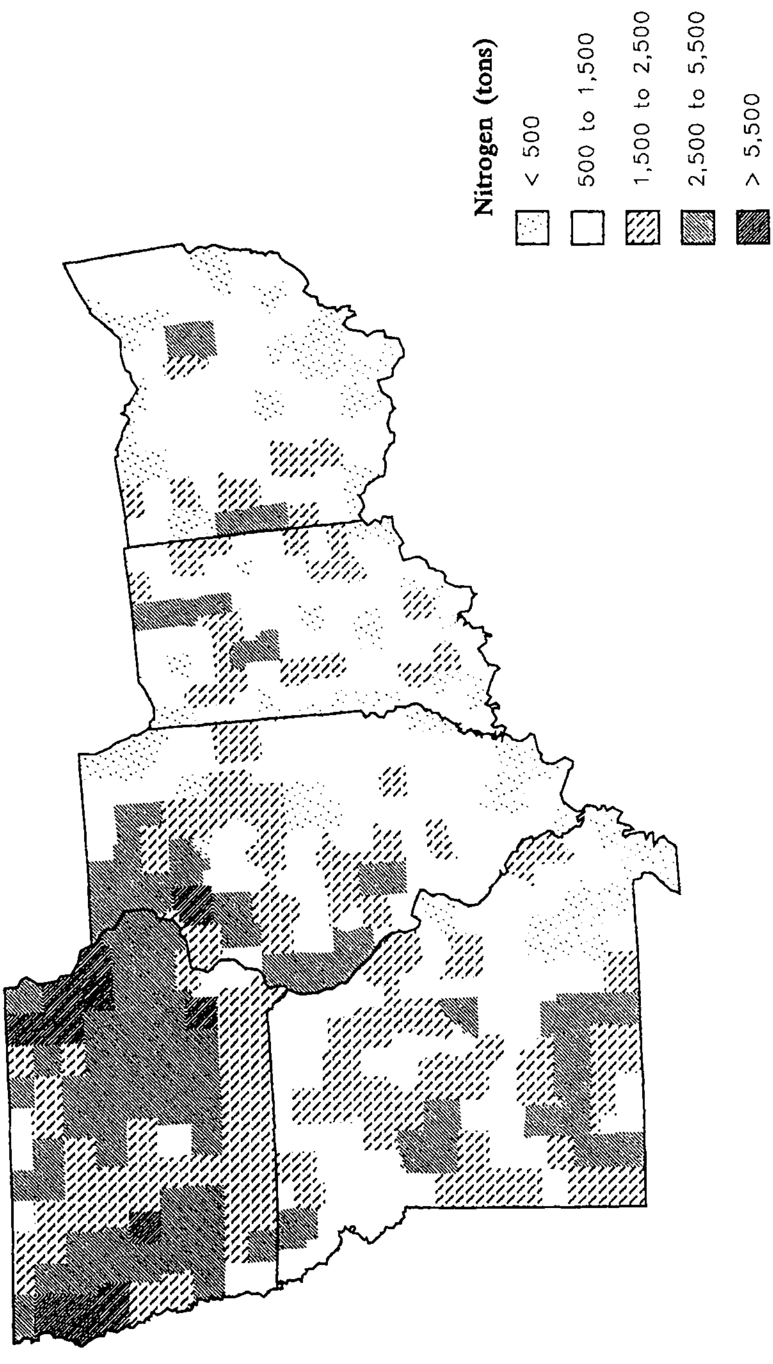

Figure 2. Loadings of nitrogen from livestock manures (estimated from livestock inventories) in the U.S. Corn Belt region, 1987.

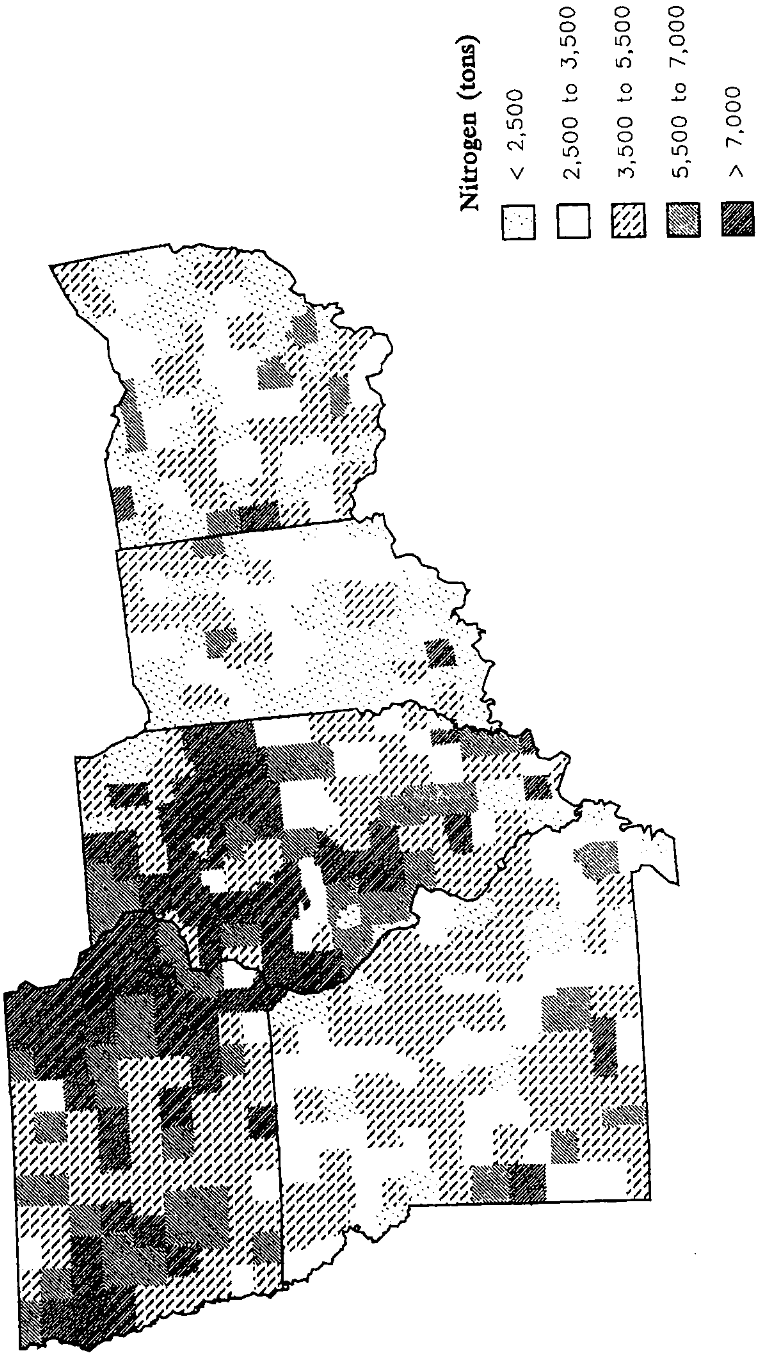

Figure 3. Loadings of residual nitrogen from all sources in the U.S. Corn Belt region, 1987.

Table 9

Nitrogen fertilizer applied and uptake by crop for the 117 grain/livestock farms in 1987.

Region	Nitrogen uptake					Nitrogen fertilizer	
	Corn	Wheat	Sorghum	Oats	Total	Applied	Residual
	(1,000 pounds)						
Ohio/Indiana	1,706	222	–	23	1,951	2,356	405
Iowa/Missouri	1,406	66	12	8	1,491	2,017	526
Illinois	951	82	8	7	1,048	1,471	423
Total	4,063	370	20	38	4,490	5,844	1,354

23.2% of nitrogen applied in the form of fertilizer and available from soybean and alfalfa credits in the sample of farms surveyed is in excess of what is needed by crops. Nitrogen from fertilizer and soybean and alfalfa credits is in excess by 28.8% in Illinois, 26.1% in Iowa/Missouri, and 17.2% in Ohio/Indiana.

Livestock nitrogen was calculated by multiplying estimated animal units by the nitrogen loading factors provided in table 2. While animal inventories by species were not reported in the survey, sales by species were reported. Thus, we estimated livestock populations by dividing livestock sales, by species, by price per head or hundred weight, converting hundred weights to live animal units. Calculation of nitrogen produced from slaughter pig production, the dominant livestock activity, serves as an example. To derive an estimate for one slaughter pig, we divide slaughter pig sales by $51 per hundred weight, the prevailing price per hundredweight, and multiply by 2.4, the prevailing slaughter weight, in hundreds, per slaughter pig in 1987 [35]. The information in table 2 indicates that one pig accounts for 32 pounds of nitrogen per year. However, since slaughter pigs remain on the farm only 6 months, the amount of nitrogen produced by a pig in six months is 16 pounds. Thus, a farm producing pigs for slaughter in a particular year also produces nitrogen that amounts to estimated slaughter pigs times 16. Nitrogen produced in manure from beef cattle and chicken production was calculated in a similar fashion. The sample did not contain an observation on dairy production. Table 10 summarizes total nitrogen production from manure for the sample.

The amount of nitrogen from livestock manure shown in table 10 is about one-fourth the amount available from inorganic fertilizer and soybean and alfalfa nitrogen credits. Put another way, the amount of nitrogen from livestock manure is 40% of the calculated uptake by corn (60% of corn uptake in Illinois). The calculations in table 9 indicate that crop production is using excess quantities of nonmanure nitrogen. The addition of manure adds an amount of nitrogen that increases in aggregate what can be absorbed by crops.

Table 10

Nitrogen produced from livestock manure for the 117 grain/livestock farms in 1987.

Region	Nitrogen (1,000 pounds)	Share of fertilizer and soybean and alfalfa credits (%)
Ohio/Indiana	614	26.1
Iowa/Missouri	488	24.2
Illinois	562	39.9
Total	1,664	28.5

Table 11

Nitrogen use, uptake, and residual nitrogen for the 117 grain/livestock farms in 1987.

	Use					Residual		
Region	Livestock	Organic credits	Inorganic	Total	Uptake	Total	#/Ac	Share (%)
		(1,000 pounds)						
Ohio/Indiana	614	220	2,136	2,970	1,951	1,019	58	34.3
Iowa/Missouri	488	142	1,875	2,505	1,491	1,014	67	40.5
Illinois	562	62	1,409	2,033	1,048	985	92	48.4
Total	1,664	424	5,420	7,508	4,490	3,018	69	40.1

Calculation of a comprehensive crop/livestock nitrogen balance (see table 11) reveals that residual nitrogen varies significantly by location in the Corn Belt sample, driven by both crop and livestock sources of nitrogen. Of the total nitrogen applied on the survey farms, 40.3% is in excess. The residual amount of nitrogen varies from 34.3% on Ohio/Indiana farms to 40.5% on Iowa/Missouri farms, and 48.5% on Illinois farms. Residual amounts of nitrogen per acre equal 92 pounds in Illinois, triple the per acre level in Ohio/Indiana, and double the per acre level in Iowa/Missouri.

Table 12

Nitrogen use, uptake, and residual nitrogen for Ohio/Indiana grain/livestock farms.

Livestock sales (dollars)	Corn harvested (acres)	Use: Live-stock	Use: Organic credits	Use: Inorganic	Use: Total	Uptake*	Residual: Total	Residual: lbs/acre	Residual: Share (%)
		(pounds of nitrogen)							
407	150	52	3,990	28,500	32,542	19,835	12,707	85	39
2,011	720	108	6,076	154,800	160,984	99,176	61,808	86	38
3,310	168	467	2,413	28,560	31,440	22,720	8,720	52	28
3,600	180	123	4,653	36,810	41,586	27,048	14,538	81	35
4,500	100	588	0	9,450	10,038	11,486	0	0	0
4,907	105	263	6,790	7,361	14,413	14,200	213	2	1
6,200	100	332	0	5,370	5,702	11,721	0	0	0
6,908	103	964	8,710	0	9,674	14,858	0	0	0
7,171	100	937	2,842	20,000	20,937	13,524	10,255	103	49
12,826	149	686	3,773	10,300	14,759	18,032	0	0	0
13,569	105	1,768	525	4,956	7,249	9,467	0	0	0
15,900	158	855	0	18,818	19,673	18,519	1,154	7	6
17,000	250	803	6,264	43,750	50,816	31,556	19,260	77	38
18,000	300	963	0	46,020	46,983	32,458	14,526	48	31
28,941	625	3,783	0	84,313	88,096	73,255	14,841	24	17
30,165	230	1,614	4,773	30,774	37,162	28,851	8,310	36	22
36,000	160	4,680	0	18,800	23,480	11,540	11,940	75	51
36,195	202	1,937	5,768	12,322	20,027	20,647	0	0	0
41,000	520	2,194	16,400	31,564	50,158	66,718	0	0	0
47,887	317	6,227	0	30,274	36,501	40,572	0	0	0
50,000	150	4,220	4.343	8,925	17,488	16,229	1,259	8	7
51,050	141	2,732	3,858	21,185	27,775	16,526	11,249	80	40
51,500	210	5,381	5,000	1,100	11,481	18,934	0	0	0
67,000	250	3,974	17,800	7,763	29,536	36,064	0	0	0
70,000	500	9,150	5,206	100,750	115,106	45,080	0,026	140	61
74,500	100	10,577	2,690	17,500	30,767	9,467	21,301	213	69
85,400	400	11,602	0	56,000	67,602	28,851	38,751	97	57
99,800	150	12,016	3,600	17,250	32,866	18,934	13,932	93	42
99,915	108	12,987	2,710	13,634	29,331	6,185	23,146	214	79
106,506	572	17,132	0	18,620	35,750	55,223	0	0	0
106,906	138	11,775	3,964	9,605	25,344	19,907	5,437	39	21
107,603	690	5,758	9,248	99,360	114,366	93,316	21,050	31	18
119,753	412	6,410	11,399	80,340	98,149	45,488	52,662	128	54
123,602	609	26,829	0	24,360	27,585	47,825	0	0	0
134,000	150	17,420	6,469	9,900	33,789	16,635	17,155	114	51
139,245	375	14,127	15,190	14,063	44,099	50,715	0	0	0
142,301	162	19,070	0	27,378	46,448	22,378	24,070	149	52
173,000	600	22,614	0	39,996	62,610	86,554	0	0	0
187,247	289	24,336	7,571	41,183	73,089	34,379	38,710	134	53
207,713	698	12,459	13,034	136,110	161,602	81,811	79,791	114	49
229,928	150	29,887	5,830	16,785	52,502	17,743	34,759	232	66
240,000	340	31,373	0	66,980	98,353	33,359	64,993	191	66
349,172	560	38,929	0	85,162	124,091	63,112	60,979	109	49
400,100	635	21,409	10,214	91,440	123,063	37,754	85,308	134	69
405,502	250	21,697	6,387	61,950	90,034	18,843	71,191	285	79
410,154	708	51,157	11,285	115,970	178,412	103,219	75,193	106	42
495,419	600	26,059	0	96,000	122,509	75,734	46,775	78	38

* Where nitrogen uptake is greater than the apparent use, residual nitrogen is imputed as zero. This apparent imbalance implies measurement errors in uptake or, more likely, in use of organic and inorganic nitrogen; i.e. it implies mining of organic sources (especially from soybeans) of nitrogen in the soil.

** Assumes nitrogen use on wheat, sorghum and oats is in balance.

Table 13

Nitrogen use, uptake, and residual nitrogen for Iowa/Missouri grain/livestock farms.

Livestock sales (dollars)	Corn harvested (acres)	Use: Live-stock	Use: Organic credits	Use: Inorganic	Use: Total	Uptake*	Residual: Total	Residual: lbs/acre	Residual: Share (%)
		(pounds of nitrogen)							
1,296	200	228	0	26,200	26,248	27,950	0	0	0
3,560	480	468	10,847	35,000	46,315	43,277	3,038	6	7
3,919	573	184	6,069	90,725	96,978	73,876	23,102	40	24
7,700	280	692	0	84,000	84,692	32,458	52,235	187	62
10,500	152	562	3,142	16,720	20,424	15,075	5,349	35	26
19,000	105	1,017	57	18,900	19,197	14,390	5,584	53	29
19,920	350	1,017	6,151	56,000	63,168	22,089	41,079	117	65
21,021	110	1,014	0	13,805	14,819	11,901	2,918	27	20
27,094	182	1,132	0	19,916	21,048	19,363	1,685	9	8
27,784	136	1.487	4,336	17,000	22,822	11,360	11,462	84	50
28,601	398	1,773	0	38,704	40,477	44,855	0	0	0
30,069	147	1,609	0	22,050	23,659	17,897	5,762	39	24
31,000	400	4,052	5,600	52,000	56,052	54,096	7,556	19	13
34,010	215	1,766	8,997	32,250	43,013	25,200	17,813	83	41
38,596	106	5,045	2,813	15,900	20,945	15,100	8,658	82	41
40,000	241	5,229	0	36,150	41,379	34,766	6,613	27	16
44,502	526	2,141	9,745	78,900	90,786	64,023	26,763	51	29
45,151	309	2,152	5,981	52,530	60,663	39,605	21,057	68	35
45,613	101	6,068	285	14,452	21,885	7,922	13,882	137	64
57,880	369	4,576	6,856	62,730	74,162	38,679	35,483	96	48
67,571	121	8,833	2,189	12,826	23,848	14,990	8,858	73	37
89,450	146	11,320	3,767	17,082	32,169	13,163	19,006	130	59
91,185	477	11,856	16,527	69,165	97,548	49,588	47,960	101	95
95,000	450	14,354	0	81,000	95,354	60,858	34,496	77	36
98,230	180	10,349	4,800	23,760	38,909	14,876	24,032	134	62
101,292	366	13,169	0	59,987	73,156	49,038	24,118	66	33
103,333	170	12,754	3,608	22,100	38,463	16,860	21,603	127	56
122,606	230	16,324	0	39,100	55,424	32,764	22,660	99	41
136,860	104	17,797	3,185	18,133	39,114	10,368	11,603	276	73
152,772	160	10,728	3,432	32,000	46,160	25,966	20,194	126	44
154,000	100	10,171	4,223	12,000	26,217	9,016	17,377	174	66
179,157	1,100	23,419	0	165,000	188,419	94,217	94,202	86	50
195,730	310	27,843	5,984	34,924	68,151	36,064	32,687	105	48
271,200	200	12,700	5,189	10,800	28,689	18,032	10,657	53	37
395,701	377	53,098	4,670	67,860	125,628	46,999	78,630	209	63
460,000	425	24,614	4,488	51,000	75,614	42,533	37,569	88	47
591,790	647	47,843	6,529	9,058	63,430	70,000	0	0	0
884,155	811	45,720	5,606	133,260	184,586	102,368	82,218	94	45
1,360,790	550	72,814	15,905	106,854	195,573	84,300	111,273	202	57

* Where nitrogen uptake is greater than the apparent use, residual nitrogen is imputed as zero. This apparent imbalance implies measurement errors in uptake or, more likely, in use of organic and inorganic nitrogen; i.e. it implies mining of organic sources (especially from soybeans) of nitrogen in the soil.

** Assumes nitrogen use on wheat, sorghum and oats is in balance.

Table 14

Nitrogen use, uptake, and residual nitrogen for Illinois grain/livestock farms.

		Use					Residual		
Livestock sales (dollars)	Corn harvested (acres)	Live-stock	Organic credits	Inorganic	Total	Uptake*	Total	lbs/acre	Share (%)
		(pounds of nitrogen)							
1,210	114	65	0	21,956	22,021	13,876	8,146	71	37
3,690	250	197	3,929	30,000	34,126	22,540	11,586	46	34
12,411	140	664	1,158	10,147	11,969	13,885	0	0	0
15,400	185	803	0	27,400	28,203	18,934	9,269	50	33
20,890	210	1,118	3,482	47,670	52,270	18,472	33,798	161	65
23,106	111	2,945	2,499	14,022	19,197	5,004	14,461	130	74
23,445	233	4,247	0	26,946	31,193	21,007	10,186	44	33
23,700	118	1,268	2,501	18,880	22,649	15,691	6,959	59	31
32,000	313	4,160	0	44,603	48,763	33,864	14,898	48	31
39,162	208	4,364	5,327	32,650	42,430	30,943	11,397	55	27
39,520	320	5,711	6,277	59,213	64,924	37,867	33,333	104	51
44,800	346	6,476	0	59,270	65,745	38,994	26,751	77	41
50,828	320	4,888	0	54,290	59,178	26,124	33,054	103	56
61,000	400	8,490	0	80,000	88,490	45,080	43,410	109	49
75,000	150	4,013	1,618	9,450	15,082	14,876	205	1	1
75,592	218	12,751	0	39,108	51,859	19,851	32,007	147	62
94,800	125	11,955	3,036	22,500	37,491	14,088	23,403	187	62
95,283	300	12,389	0	50,100	62,489	30,835	31,654	106	51
119,952	193	8,047	3,241	32,036	43,324	26,778	16,546	86	38
126,145	565	17,184	0	92,720	109,904	73,624	36,640	65	33
138,900	625	7,432	13,075	52,500	73,008	78,890	0	0	0
170,297	124	22,139	0	20,522	42,661	6,275	36,386	293	85
186,300	315	24,353	0	63,630	87,983	39,761	48,222	153	55
191,143	117	8,199	2,013	3,600	6,516	13,813	0	0	0
210,781	650	11,279	11,261	106,600	129,139	69,784	59,355	91	46
268,829	231	38,362	0	13,245	129,139	23,951	27,655	120	54
312,000	697	25,342	0	110,757	51,606	82,402	53,698	77	39
450,145	375	40,548	8,100	73,400	122,048	47,979	74,070	198	61
1,100,000	303	279,661	868	54,540	335,069	53,465	281,604	927	84

* Where nitrogen uptake is greater than the apparent use, residual nitrogen is imputed as zero. This apparent imbalance implies measurement errors in uptake or, more likely, in use of organic and inorganic nitrogen; i.e. it implies mining of organic sources (especially from soybeans) of nitrogen in the soil.

** Assumes nitrogen use on wheat, sorghum and oats is in balance.

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